FINAL REVIEW OF NORTHMET MINE SITE MODFLOW MODEL

NORTH ATLANTIC DIVISION REGIONAL CENTER OF EXPERTISE FOR GROUNDWATER MODELING

PHILADELPHIA DISTRICT, US ARMY CORPS OF ENGINEERS

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EXECUTIVE SUMMARY

This document provides an assessment of the mine site MODFLOW model developed by PolyMet contractor Barr Engineering to estimate groundwater flows to the NorthMet mine pits during operations. The purpose of this review was to provide an independent evaluation of the input parameters to the model, the extent to which the model aligns with generally accepted industry practices, and the conclusions of the model. This review also discusses additional, related issues that have been raised by other reviewers, including the possibility for northward groundwater flow from the NorthMet mine pits to the Peter Mitchell pits after closure.

The review concludes that, while there are numerous uncertainties in the model, it is generally sufficient for the purpose for which it has been developed, namely, to estimate groundwater flows to the pits as one component of the volume estimate used to design and size a water treatment plant. Recommendations are made for reducing or quantifying these uncertainties and improving the defensibility of the model, but it is not expected that action on these recommendations will have a significant impact on the design of the treatment plant.

Other reviewers have used this model as one component of their argument for additional study into the possibility of post-closure northward flow. This review concludes that the model, in its current form, is not an appropriate tool for this analysis. Recommendations are made for improving the model such that it may be used to investigate northward flow. Uncertainties will still remain, however, and significant sensitivity analysis would be required as outlined in the recommendations section. Additional modeling with sufficient sensitivity analysis may be able to eliminate the concern about northward flow with the existing data, or it may help determine what data would be most important to collect for a more precise estimate of possible northward flow rates.

These recommendations for future modeling are not intended to imply that the U.S. Army Corps of Engineers intends to model or analyze northward groundwater flow at this site. This task is outside the scope of the Corps' Section 404 permit authority under the Clean Water Act. All comments and recommendations are provided for informational purposes only and as a possible guide for future work which may be undertaken by others.

Because this model has been used by outside reviewers to investigate northward flow, this review also includes a summary of the arguments for and against the development of northward flow after closure of the mine pits.

INTRODUCTION

The Philadelphia District (NAP) of the US Army Corps of Engineers (USACE) was requested by the St. Paul District (MVP), USACE to provide an independent review and evaluation of the MODFLOW model developed by Barr Engineering for the proposed NorthMet mine site. NAP houses some members of the USACE North Atlantic Division Groundwater Modeling Regional Center of Expertise (RCX). The reviewers were asked to primarily review the input parameters for the model, ensure the model aligns with generally accepted practices and to comment on the use of varying versions of MODFLOW during the modeling process.

This review proceeded in three separate steps. During Step 1, NAP modelers reviewed documents provided by Barr Engineering and MVP along with model input and output files provided by Barr Engineering. Although hundreds of documents were provided, the first step of the review focused on the following documents:

- Groundwater Modeling of the NorthMet Mine Site, December 2014 (modeling report)
- RS 02 – Hydrogeologic Investigation – Phase I, Draft-02, November 2006
- RS 10 – Hydrogeologic Investigation – Phase II, Draft-02, November 2006
- RS 10A – Hydrogeologic Investigation – Phase III, March 2007
- Hydrogeology of Fractured Bedrock in the Vicinity of the NorthMet Project, December 2014 (hydrogeology report)
- NorthMet Project, Water Modeling Data Package Volume 1 – Mine Site, Version 14, February 2015
- RS 22 – Technical Detail Report, Mine Waste Water Management for the PolyMet NorthMet Mine Site, Draft-02, October 2007
- RS 52 PolyMet Technical Design Evaluation Report, Mine Closure Plan Report, July 2007

For Step 2, MVP set up a meeting between NAP modelers and Barr Engineering modelers to discuss the developing comments and to allow Barr to provide clarification on some of the issues identified. This meeting took place on October 27, 2015 in St. Paul, MN and was also attended by representatives from TetraTech and PolyMet. Documents and figures viewed during the meeting were then provided to NAP for reference.

Additional documents provided subsequent to the meeting included:

- Appendix K: Mine Site MODFLOW Model Baseflow Sensitivity, January 2015a
- Response to Cooperating Agency Comments Related to Peter Mitchell Pit – Version 4, September 2015
- Response to Cooperating Agency Comments Mine Site MODFLOW Model – Version 2, July 2015
- Draft Figure – Simulated Heads Compared With Ground Surface and Wetlands Extents, October 2015
- Draft Figure – Groundwater Flow Between Layers 1 and 2 Under Current Conditions, October 2015

This face-to-face meeting was followed up with two conference calls to discuss the model comments in greater detail. During this period, Barr provided the GoldSim model to NAP reviewers for reference and high-level consideration. Because the emphasis of this assessment was on the MODFLOW model, the GoldSim model was not reviewed in detail. The draft memo was updated and delivered in November 2015.

During Step 3, MVP provided NAP with comments from other reviewers and NAP used that information to finalize the model assessment. The new information included memos, emails and figures from the Great Lakes Indian Fish and Wildlife Commission (GLIFWC), the Grand Portage Band of Chippewa Environmental Department and Tom Myers, a consultant for Minnesota Center for Environmental Advocacy (MCEA). Also included, were a number of memos by the co-lead agencies or Barr, responding to some of the comments.

MODEL PURPOSE

An important first step in developing a model is to determine and agree on the purpose and objective of the model. When this purpose is well-defined, it will guide the selection of assumptions and simplifications and help in the judgment of the appropriateness of the model (Anderson, Woessner and Hunt, p.27, 2015). As stated in the modeling report and reiterated during the October 2015 meeting with Barr Engineering, the purpose and objective of this groundwater model was only to predict the amount of groundwater expected to flow into the mining pits during operations and at various points in the filling period. These predictions were used along with other flow models and estimates to size the wastewater treatment facility.

The reviewers learned during the October 2015 meeting with Barr Engineering that the groundwater flow to the pits is only a small portion of the water expected to require treatment, with the main sources being precipitation and surface run-off in both the pits and the stockpiles. Annual average flows are shown in Figures 6-7, 6-13 and 6-19 of the Water Modeling Data Package (Barr, 2015b). The reader should note that short-term flow rates from non-groundwater sources will most certainly be higher during precipitation events and, especially, rapid snow melt periods. Thus, a relatively large variability in the groundwater component of the flow volumes is acceptable and will not significantly affect the calculations of total volumes or the design capacity of the treatment facility. Also, the treatment facility has been designed to be modular, and the volumes of water to be treated will increase slowly over a number of years before reaching maximum, so there will be plenty of warning, if predictions are low, to add additional modules to the treatment facility.

Reviewer comments, most notably those from GLIFWC, provide long lists of quotes from draft versions of the Environmental Impact Statement (EIS) with references to data derived from the MODFLOW model beyond the inflow to the pits. These include rock/soil parameters such as hydraulic conductivity and flow parameters such as gradients and flow paths. As these statements have been largely removed from the FEIS and since they are contrary to direct communication from the Barr modelers, these statements in the draft EIS documents are believed to represent editorial oversights, not true statements of the purpose and use of the model. In an effort to clarify which parameters or data were obtained from the MODFLOW model, the following table lists the parameters or information originally stated to have come from the MODFLOW model with comments on the actual source of these parameters based on more recent documents or discussions with Barr modelers.

Parameters / Data Stated (in Barr Draft Reports) to have Come from MODFLOW Model	Comments from NAP on Actual Source of the Parameters / Data
General groundwater head distribution; Groundwater flow conditions following pit closure	This model is not an appropriate tool for investigating or predicting drawdown due to operations dewatering or flow conditions post-closure. It is unclear how these predictions were used in or affect the final conclusions of the FEIS.

Parameters / Data Stated (in Barr Draft Reports) to have Come from MODFLOW Model	Comments from NAP on Actual Source of the Parameters / Data
Establishing contaminant flow paths	The flow paths have apparently been set up to lead from possible areas of contamination downgradient to exit points (notably the Partridge River). The northward flow path from the pits was not investigated in the GoldSim model. Whether this was because the model did not show a northern flow path, or because the modelers did not expect one to exist based on their knowledge and understanding of the hydrogeology at the site, is unclear. See the section on Northward Flow in this memo for an analysis of the arguments for and against northward flow.
Gradients along flow paths	According to the Water Modeling Data Package (2015, section 5.2.3.1) and personal communication with Barr engineers, the gradient was developed using the river stage, pit water level elevation and horizontal distance, not the model results.
Hydraulic conductivity along flow paths	According to the Water Modeling Data Package (2015, section 5.2.3.3), the hydraulic conductivity used in the GoldSim model for the surficial aquifer was a triangular distribution with the mode set using the recharge from the XP-SWMM model and gradient. (We note that there is disagreement on the recharge value, which is discussed later in this document.) For the Duluth complex, the mode was set to 3×10^{-3} m/d. None of these values match the MODFLOW model calibrated values, so they cannot have been taken from the model.
Infiltration/Recharge along flow paths	Recharge along the flow paths was calculated by dividing the baseflow by the watershed area. (We note that there is disagreement on the baseflow value, which is discussed later in this document.)
Pit inflows	Calculation of pit inflows was the main purpose for the MODFLOW model.
Porosity along flow paths	The listing of the MODFLOW model as the source for the porosity value appears to be an error. Porosity is neither an input to, nor an output of a steady state flow model. The Water Modeling Data Package (2015, section 5.2.3.3) states that a value of 0.3 was used for the surficial deposits and a value of 0.05 was used for the bedrock flow paths. These values are reasonable.

Many of the comments from other reviewers provided in Step 3 are similar in nature to comments that have been listed below as part of Steps 1 and 2 of this review. Several of the comments do not directly impact the purpose of the model – to estimate flow to the pits during operations – for reasons described below. Some of the comments are based on the use of the model to investigate northward flow from the NorthMet pits towards the Peter Mitchell pits. The use of the Barr mine site MODFLOW model to investigate northward flow is inappropriate and beyond the design and capacity of the model. Consequently, it was considered beyond the scope of this review to comment on the controversy until Step 3. (In fact, the controversy was unknown to NAP reviewers at the beginning of the review process.) However, as a northward flow path has not been included in the GoldSim transport analyses, possibly because the MODFLOW model does not predict such flow, this review will address these concerns by analyzing the arguments for and against northward flow and making recommendations for future modeling work which might better simulate closure conditions between the two mines.

SUMMARY

As far as its stated purpose (to investigate groundwater flows to the pits during operations) the NorthMet mine site model generally followed accepted practices including:

- The modelers used their best efforts to obtain field data to support the input parameters. When not available, literature values were used to fill data gaps (Anderson, Woessner and Hunt, p. 236, 2015). Although Grand Portage raised concerns with the amount of data gathered and stated that other similar mining projects have required significantly more data for the FEIS, it seems that the lack of data in some areas is due to difficulties accessing the land. Comments on this subject are beyond the scope of a groundwater model review. This review has been developed based on the available data with a view to making best use of that data.
- The automated parameter estimation code, PEST, is commonly used in the industry and was constrained using the available field data. (Anderson, Woessner and Hunt, pp. 414-420, 2015)
- Many of the uncertainties in the model have been investigated using sensitivity analyses. (Anderson, Woessner and Hunt, pp. 458-460, 2015)
- The results of the MODFLOW model were input to a MonteCarlo analysis using the GoldSim modeling software, which incorporates the uncertainties and provides a range of possible outcomes. (Anderson, Woessner and Hunt, pp.469-476, 2015).
- In the absence of suitable boundary locations near the mine site, the specified head boundary conditions were set based on the results of a regional model which extended 10 to 20 miles in each direction. (Anderson, Woessner and Hunt, pp 159-161). Note that the regional model was not evaluated as part of this review.

The following sections point out areas where there was less certainty in the input parameters, especially where this uncertainty may have impacted the predictions and recommendations of the model. Many of these uncertain parameters have been investigated using sensitivity analyses which were presented in the October 2015 meeting. The following sections reflect the evolving understanding of the review team.

This model is not valid for investigating or predicting flow paths from the pits, drawdown during dewatering or post-closure groundwater conditions. The majority of the uncertainties discussed in this review have little impact on the flow calculations for the purpose of sizing a treatment plant, but may have significant impact on other uses for the model.

There is no concern on the part of the NAP review team with the use of different MODFLOW versions as the modeling project progressed. The US Geological Survey (USGS, author of MODFLOW) is known for detailed review and robust testing of all products before they are released to the public. The later versions of MODFLOW contain more options, but do not provide different or more accurate solutions if the old options are used. The Step 3 information included an email from Randy Hunt, USGS (4/15/2015) stating that current versions should always be used because of the possibility that bugs may be identified, but not fixed, in older versions. His argument has merit; however, the calibration model provided by Barr Engineering, which was originally developed in MODFLOW-96, was easily rerun in MODFLOW-2000 and MODFLOW-2005 by the NAP reviewers and provided nearly identical results. Any differences would be well within the range of errors due to discretization, data gaps, etc. The use of

MODFLOW-NWT was necessary in the dewatering models as it contains a newer solver which can better handle dewatering and rewetting of model cells. Previous solvers would not have been able to solve the problem at hand without extensive simplifications or the breaking of the problem into numerous pieces.

CAVEATS

Hundreds of documents and model files were provided to the reviewers. Review focused on the model files and the few documents (listed above) deemed to be most useful to meeting the requirements of the review. Not all documents (including those above) were read in detail in their entirety. It was also impossible to check every value and modeling decision. Focus was placed on determining if the model results aligned with the conceptual site model and if the assumptions used in the modeling were reasonable with respect to the purpose of the model and the predictions to be made by the model output. The reviewers used the model files to become familiar with the model set up and the sensitivity of many of the input parameters, but could not test all of them. In completing the review, some assumptions were made, including the following:

- The depths of the geologic contacts between the bedrock units were assumed to be accurate. Neither the modeling report nor the hydrogeologic studies discussed how the contacts were placed. As most of the groundwater flow is expected to be near the ground surface, these contacts should be of little importance, especially at depth.
- The regional model was not evaluated. A brief discussion of the regional model was provided in the modeling report, but the MODFLOW files were not provided.
- The wetlands delineation is assumed to be accurate. Locations of wetlands impacted the assignment of recharge and hydraulic conductivity in the upper layer.
- Although the GoldSim model was provided, it was not evaluated in detail. Conversations with the Barr Engineering modeling team were used to understand the use of the MODFLOW output in the GoldSim model and in the design of the project features.

MODEL GUI

MODFLOW is an open-source freely-available groundwater modeling code developed by USGS. It is very commonly used and well-respected in the industry. Setup of the MODFLOW modeling files can be cumbersome without the use of a graphical user interface (GUI). Although USGS supports their own GUI, several other commercial GUIs have been developed and are commonly used to setup MODFLOW models and analyze the results. Barr Engineering used Groundwater Vistas, developed by Environmental Simulations, Inc. NAP generally uses GMS (Groundwater Modeling System), developed by Aquaveo. Both GUIs are well-respected and used by millions of MODFLOW users throughout the world. Although both use the same MODFLOW code to solve the groundwater equations, there can be minor differences in the model results generally due to interpolation, display options or slightly different calculation methods for input parameters. Further, in porting the model to GMS, some data, which is not provided in the MODFLOW files (such as grid origin and rotation, for example), was estimated. This may result in slight differences in the numbers reported here and those reported by Barr Engineering. These differences are minimal and well within the error inherent in the model results.

MODPATH

MODPATH is a USGS particle tracking code that works on the output from the MODFLOW model to illustrate flow directions. To run MODPATH, the user selects locations for particles, then the code uses the velocity vectors from the MODFLOW results to determine where the particle would flow. Particles can be set to flow forward (towards the point where the particle exits the model) or backwards (towards the point where the particle enters the model). In this review, MODPATH was used several times to visualize the movement of water in the MODFLOW model. Although MODPATH can calculate travel times, that option was not used in this analysis. The particle tracks were only used to visualize where groundwater would be expected to move based on the MODFLOW model output.

UNCERTAIN INPUT PARAMETERS

BASEFLOW ANALYSIS

Original Analysis (Steps 1 and 2)

The inclusion of flow measurements in a groundwater model can lead to more defensible calibrations and a unique solution. This is especially important in models dominated by specified head boundary conditions whose purpose is to predict flow rates. However, the basis of the flow calibration values for the Partridge River in the NorthMet model relies on output from another model (XP-SWMM) and not field measurements. The information provided seems to indicate that the XP-SWMM model was calibrated to a single USGS gage, which is located at least 15 miles downstream of the area of interest. The XP-SWMM calibration was apparently to only three years of gage data which were available during periods when the Peter Mitchell pits were not dewatered. Although considerable effort was made to show that this short period could represent a typical year by comparing it to nearby river basins with longer periods of record, this still represents a significant source of uncertainty. Further, the baseflow is compared to flow in and out of the model through the Partridge River which is only generally modeled with stages estimated from LiDAR. It was also noted that while the MODFLOW calibration model shows flow from the groundwater to the river (baseflow) in many locations, it also shows flow from the river to the groundwater in other places.

Barr Engineering performed a sensitivity analysis on the baseflow by increasing the baseflow estimate by a factor of 4 and recalibrating the model (Barr, January 2015a). At the same time, recharge was also increased by a factor of 4. Note that this change brought the modeled recharge rate much closer to the USGS (2007) estimated rate described in the Recharge section below. The recalibrated model required the hydraulic conductivity in the unconsolidated deposits to be doubled on average. There were also minor increases in the hydraulic conductivity of the bedrock materials. Increases in the vertical hydraulic conductivity of streambed deposits also increased by a percentage ranging from 7% to nearly 900%. With these adjustments, the flow to the East Pit during operations increased by 12% to 41% during each of the first 19 years of operations. Year 20 flows nearly doubled. Many of the flows to the Central and West Pits doubled or tripled during operations when the changes were made. Despite the large percentage changes reported, this change in flow volume was reported to be insignificant compared to the water entering from precipitation and runoff which would pass through the treatment facility.

In terms of the purpose of this model (estimates of groundwater flow to the pits) these sensitivity analyses indicate that the impact of possible uncertainties in baseflow estimates or the modeling of the Partridge River do not have a significant impact on the rate of water flowing to the treatment facility compared to other water sources.

Update (Step 3)

The original baseflow estimates (0.51 cfs at SW003) were based on an XP-SWMM model calibrated to data at a gage located 17 miles downstream with data from nearly 3 decades ago. The baseflow estimate is further complicated by the addition of dewatering flows from the Peter Mitchell pits.

Several reviewers have made their own estimates of baseflow, including:

- An email from John Coleman, GLIFWC, dated June 12, 2012, provided statistics on flow measurements at the Dunka Road gage (SW003) including, Q70 of 6.9 cfs, Q90 of 2.8 cfs, and minimum 7 day average of 2.37 cfs. He acknowledges that the flow values are based on less than a year of data and that the rating curve is still being developed. (GLIFWC, 2012)
- An email from John Coleman, GLIFWC, dated July 2, 2013 proposed baseflow estimates for SW003, including 2.32 cfs (Q90 from May 2011 – April 2013), 1.9 cfs (Q90 for May 2011 – December 2012 accounting for ice), 1.8 cfs (Q90 for July – September 2011 when Northshore was not pumping) and 1.1 cfs (Q90 for February – April 2012 when Northshore was not pumping). (GLIFWC, 2013)
- A DNR memo from Greg Kruse, dated December 17, 2013, proposes a range of 1.3-1.8 cfs for the Dunka Road location (SW003). This range is based on baseflow separation for data on a new gage from June 2011 – December 2012. The memo acknowledges that this estimate is suspect because of limited data, influence from North Shore pumping and the severe to extreme drought conditions at the time the data was collected. (MNDNR, 2013)
- Grand Portage comments on the FEIS, submitted December 21, 2015 stated that the minimum baseflow measured by the MNDNR for data collected January 25-26 and February 15-16, 2011 was 3.4 cfs. The location for these measurements is unclear. The comments state that it was measured "by the MNDNR in the Partridge River at the point nearest the proposed mine pits." (Grand Portage, 2015)
- Tom Myers, a consultant for MCEA developed a groundwater model and recalculated baseflow at the Colby Lakes gage at 21.7 cfs (Myers, 2014). The location of the gage appears to be outside the Barr model boundaries, but may coincide with SW006 where Barr estimated a baseflow of 5.3 cfs. This makes the Myers estimate about 4 times greater than the Barr estimate. If a similar ratio is applied to the baseflow at SW003, it would be about 2 cfs, which is in the range of the other reviewers' estimates listed above.

All of the estimates of baseflow listed above and the estimate proposed by Barr and used in the calibration of the MODFLOW mine site model suffer from shortcomings including small datasets, the difficulty of separating out Northshore pumping flows, and in some cases, distance from the site and age of data. Some of the estimates have attempted to correct for these inadequacies in the data or argue that the limitations do not impact the results. Although baseflow does not typically vary to the degree that surface water contributions fluctuate, it is impacted by seasonal variations and regional groundwater conditions (e.g. droughts), so long-term average baseflow values are generally used.

Barr has shown through sensitivity analysis that increasing the baseflow by a factor of 4 does not significantly impact the groundwater flow to the pits during operations (Barr, January 2015a). Barr also indicates that a similar change to baseflow did not impact the contaminant loads calculated for the Partridge River in the GoldSim model (Barr, January 2015b). (Note that this review did not assess the GoldSim model.) In the absence of sufficient recent data near the project site, it is recommended that any future modeling or calculations for any other purpose include several sensitivity analyses of this parameter covering the entire range of proposed values.

PETER MITCHELL PITS

Original Analysis (Steps 1 and 2)

The Peter Mitchell mine pits are located just north of the NorthMet mine location and are included in the model as constant head boundary conditions. It is unclear from the report how the assigned heads were determined but their shapes and locations are reasonably consistent with aerial photos available from Google Earth and ESRI. Historical imagery on Google Earth shows significant dewatering in one pit (Area 003 East) occurring gradually between about 2006 and 2009 with the dewatered level being maintained until the most recent photo (see Figure 1). The model was calibrated to head data obtained between 2005 and 2013 with the majority of the bedrock data being based on single measurements in December 2006. These pits constitute significant sources of water to the model, providing over 20% of the inflows to the model, and have the potential to influence heads at the observation points

The calibration model indicates that a large part of the water in the upper reaches of the Partridge River comes from the Peter Mitchell Pits via groundwater. There are 145 gaining river cells between the river sources and the first major (roughly 90°) bend in the river (where flows turn from largely NE to SE). Using the calibrated solution, a single MODPATH particle was placed in each of these 145 gaining river cells. MODPATH was run in reverse mode to find the source of the water entering the river from groundwater. Of those 145 particles, 62 particles came directly from the Peter Mitchell ponds, 18 came from recharge, and the rest came from losing river cells. (See Figure 2.)

Although the model results indicate that the Peter Mitchell pits are a major source of water to the area, data presented at the October 2015 meeting (Barr, 2015f, see Figure 4) showed no correlation between heads in five bedrock wells along the north side of the NorthMet pit site and the water levels in the Area 003 East Pit (Peter Mitchell). Over a period of 3 years, the pit level dropped by approximately 40 ft, while the bedrock wells experienced only small (less than about 3 ft) variations (increases and decreases). According to the Barr modelers, during this period, the Hundred Mile Swamp (located between the proposed NorthMet mine site and the Peter Mitchell pits) did not see significant effects, although this was not measured. This data indicates that, contrary to what the model shows, the Peter Mitchell pits are not the main source for the Hundred Mile Swamp, the Partridge River (except as pumped water is released in the river) or the bedrock in the area of the proposed mine pits.

In addition, it is noted that the most recent aerial photos show widely variant heads in Area 003 West and Area 003 East Pits. Barr Engineers and PolyMet personnel indicated in the October 2015 meeting that there is no cutoff wall between these two pits. The disparate head levels probably could not be maintained if the pits were the main source of water to the region as the model suggests.

These arguments indicate that the model does not correctly reproduce the source of water to the NorthMet pits, the Partridge River and, possibly, the Peter Mitchell pits. However, in the calibration model, calculated heads are above or quite close to the ground surface for much of the area between the Partridge River and the Peter Mitchell pits (Figure 3). Thus, although the model does not explicitly include the One Hundred Mile Swamp as a boundary condition, the heads in the area are likely close to reality and the gradient towards the proposed pit locations is also close to reality. Also, the model-calculated heads in the swamp area do not change by more than a few hundredths of a meter during operations and the various closure models. This is consistent with the idea that heads in the swamp are not impacted by NorthMet pit operations. It is likely that the omission of the One Hundred Mile Swamp and the incorrect hydraulic connection between the Peter Mitchell Pits and the proposed NorthMet pits, does not impact the predictions of flow to or from the pits. Some changes to the model, detailed in the final section of this report, could fix this problem and verify the minor impact to the pit flow predictions.

This incorrect modeling of the importance of the Peter Mitchell pits to the hydrogeology of the region may have significant impacts to almost any other purpose to which the model might be applied. Any changes to the model to predict possible future conditions should be checked to ensure that the water level in the One Hundred Mile Swamp is reasonable before using the model for other purposes.

Update (Step 3)

The Step 1 and 2 reviews echo comments submitted by GLIFWC regarding the Peter Mitchell pit water levels used in the model, though GLIFWC is able to provide specific data on past and future pit levels. (This data could not be independently confirmed.) While the current model is considered sufficient to estimate flows for design of a treatment plant, any future modeling or adjustments to the existing MODFLOW mine site model should be calibrated with the correct water levels in the Peter Mitchell pits. Further, any modeling to investigate groundwater conditions during closure should use the estimated Peter Mitchell pit levels in the future (approximately 1476 ft at PolyMet closure, 1300 ft at Peter Mitchell closure, and 1500 ft for long term closure). We reiterate that the use of the existing MODFLOW mine site model to investigate conditions when Peter Mitchell pits are low is not recommended.

DUNKA RIVER TRIBUTARY

Original Analysis (Steps 1 and 2)

The Dunka River tributary just northeast of the site and the Partridge River (shown in Figure 4) has not been modeled in the calibration model (or the dewatering scenarios). Although this river is separated from the mine site by the Partridge River, it is likely to take some of the groundwater falling between the two rivers and affect the flux to the Partridge River cells. If river baseflow is to be used as a calibration parameter, all impacts to the baseflow, including the Dunka River should be explicitly modeled.

Barr Engineering stated at the October 2015 meeting that this tributary to the Dunka River is locally called Langley Creek. Although this name could not be verified in the USGS Geographic Name Information System (GNIS), it will be referred to as such in this report.

Because Langley Creek is separated from the pits by the Partridge River, the main concern with the exclusion of Langley Creek from the model is the possible impact it may have on baseflow to the Partridge River. Because the sensitivity analysis has shown only small impacts to the pit flows when baseflow is changed four-fold, the addition of Langley Creek is unlikely to have significant impacts to the pit flow. This is doubly true when it is considered that the groundwater flow to the pit is small compared to other water sources to the treatment facility including surface runoff and precipitation to both the pits and the stockpiles. If, in the future, the model is used for other purposes, the impact of the exclusion of Langley Creek should be carefully considered, especially if the heads between Langley Creek and Partridge River are of importance.

INTERACTION BETWEEN UNCONSOLIDATED DEPOSITS AND BEDROCK

Original Analysis (Steps 1 and 2)

The model report indicates that interactions between the unconsolidated deposits and the bedrock are minimal. This statement seems to be based on a single USGS report from 1980, but is reasonable given the different flow mechanisms in the unconsolidated deposits vs. the fractured bedrock. The regional model was calibrated with a recharge value (to the bedrock) of 0.001 in/yr. Figure 5 shows the downward and upward flow between the bedrock and the surficial aquifer calculated from MODFLOW's cell-by-cell flow file and the cell area. The local-scale calibrated model does show infiltration to the bedrock on the order of 0.001 in/yr in some parts of the mine area where the unconsolidated deposits are underlain by the Duluth Complex. The infiltration values between layer 1 (unconsolidated deposits) and layer 2 where it represents the Duluth Complex, range from approximately 0.001 in/yr to 0.02 in/yr in the south part of the mine area. However, there are also some areas inside the mine area where the model results indicate movement of water upward from the Duluth into the unconsolidated deposits. This does not appear to be consistent with the conceptual model.

In the north part of the mine site which is underlain by the Virginia Formation, infiltration values are much larger because of the higher hydraulic conductivity of the bedrock, reaching as high as 3 in/yr. There are also, however, areas along the north of the site where the model results indicate movement of water upward from the Virginia Formation into the unconsolidated deposits at rates up to 4 in/yr. Maximum infiltration rates and flow upward in other areas of the model domain exceed 20 in/yr in some places.

A pump test at P-2 was presented in the Phase III hydrogeologic investigation (Barr, 2007a), which was designed to evaluate the connection between the Virginia formation and the unconsolidated deposits. The NAP reviewers used the calibration model to simulate the pumping test. Pumping well P-2 was placed based on coordinates provided in the calibration data by Barr Engineering. Ob-2 was moved slightly from the provided location to ensure it was in the Duluth complex cells in the grid as indicated in the report. The five observation wells were placed approximately based on the distances and directions mentioned in the report. Note that pairs of observation wells were installed at the same distance from the pumping wells but at different depths in the unconsolidated deposits. Since the model includes only a single layer for the unconsolidated deposits, both fell in the same grid cell and the model could not separate their drawdown responses. See Figure 6 for locations of the wells and results of the simulated pump test.

When the calibration model was used to reproduce this pump test, the drawdown response at Ob-2 was over-predicted by the model (measured at 1.5 m, computed at 4.0 m). Some of this discrepancy is likely due to the large cell sizes and the fact that Ob-2 is near the interface between the Virginia Formation and the Duluth Complex, which may not be modeled exactly given the large cell sizes. The response at 20P, which was screened in the unconsolidated sediments and located 50 m from the pumping well was over-estimated by the model (measured at 0.1 m, computed at 3.4 m). The response at 2P, screened in the unconsolidated sediments and located 230 m away from the pumping well was also over-estimated (no response noted in the field, computed at 1.4 m).

This simulation indicates that the communication between the Virginia formation and the unconsolidated deposits in the model may be too great. Although the cells are large for reproducing a pump test and the vertical resolution between the two units is limited, there are approximately 8 cells horizontally between P-2 and 2P and the response from the model should be similar. When combined with the large infiltration and upward flow rates between layers 1 and 2, these results may indicate a need to reevaluate how the model reproduces the interactions between layers 1 and 2.

During the discussion of the pump test at P-2 in the October 2015 meeting, Barr Engineering suggested that the One Hundred Mile Swamp may limit the drawdown in the pump test results and its exclusion from the model would explain the inability of the model to reproduce the pump test results. This is a reasonable explanation, but shows that while the model may be useful for gross estimations of groundwater flows to the pits, the model is not likely a good tool for most other purposes.

The inconsistencies between the conceptual model and the flow regime depicted in the model may affect the model's ability to answer some questions and may impact the flow predictions made by the model. However, the flows to the pits from groundwater are small compared to other flows to the treatment facility which are not captured by the model, such as precipitation and surface runoff.

Update (Step 3)

There is clearly some uncertainty about the degree of communication between the surficial aquifer and the bedrock aquifers. The conceptual model described in the modeling documents indicates little communication between the two systems, but the model seems to overestimate this communication and the Co-lead memo (NorthMet EIS PMs, October 2015) depends on significant recharge through the surficial aquifer to create the mound which would prevent northward flow. Although this issue has little bearing on the flow of groundwater to the pits during operations, it clearly is pivotal in determining the likelihood of northward flow during closure. Any models used to assess groundwater conditions post-closure should be calibrated to the P-2 pump test.

In addition, it would be prudent to run any future models with several vertical hydraulic conductivity values in the surficial aquifer to consider the possibility of close connection and less interaction between the two systems. Wetlands could be explicitly modeled as precipitation-fed or as groundwater-fed components as a sensitivity analysis.

PARTICLE TRACKING

Original Analysis (Steps 1 and 2)

The hydrogeologic report (Barr, 2014b) and the conceptual model (Barr, 2014a) indicate that nearly all the groundwater flow in the bedrock is expected to occur near the top of bedrock where fractures are more likely to occur and where they are not compressed by the weight of overlying rock. The hydrogeologic studies referenced in the modeling report indicate that there is little communication between the bedrock and the overlying deposits. Therefore, one would expect that flow paths in the MODFLOW model would be mostly horizontal and seldom venture below the upper 2-3 layers of the model. However, a MODPATH analysis where particles were placed in the middle of layer 1 and layer 2 cells shows that while many flow paths have horizontal movement towards the nearest river as expected, some flow paths proceed down to the deepest layers of the model before reversing direction and coming back up to a river cell or a boundary cell in one of the upper layers of the model. These results are shown in Figure 7.

The flow paths which lead down to the deepest layers of the model are not of concern to the purpose of the model (estimation of groundwater flows to the pits for sizing the treatment facility) because other flows to the treatment facility not captured by the model (precipitation and surface runoff) are so much larger. These flow paths, however, do not match the conceptual model and may impact results if the model is used for other purposes.

RECHARGE

Original Analysis (Steps 1 and 2)

According to the modeling report, recharge was not used as a calibration parameter, but rather, was set such that the ratio between recharge to the upland areas and wetland areas matched that used in the draft model and that the total recharge to the drainage area of the Partridge River matched the baseflow developed by the XP-SWMM. It is unclear why the recharge ratio from the draft calibration model was given so much credence. Concerns with the use of the results from the XP-SWMM were described previously.

The recharge rates used in the model are much smaller than those estimated by USGS (2007). However, these lower recharge volumes may be reasonable given the fact that a large portion of the area of concern is covered with wetlands where water only slowly enters the subsurface.

During the sensitivity analysis for baseflow, mentioned previously, the recharge was increased by the same factor as the baseflow target for re-calibration. This change brought the modeled recharge close to the USGS estimate. As described above, this adjustment resulted in a large change to the flow to the pits, but this change was not significant to the overall expected volumes passing through the treatment facility since groundwater flow is a minor portion of that flow. Precipitation and overland runoff, especially during snowmelt, are much larger contributors to the treatment facility flow.

It is recommended that recharge be used as a calibration parameter. It could be applied using the pilot points which were used for the horizontal hydraulic conductivity, or it may be loosely tied to the hydraulic conductivity of the surface layer.

Update (Step 3)

Many of the reviewers also felt that the recharge value used in the MODFLOW mine site model was too low. We agree with the co-lead agencies (Co-lead Agencies, March 2015) that recharge is a difficult parameter to estimate and that estimates such as the USGS estimates, which are generated regionally, are not always reasonable for smaller-scale models. While sensitivity analyses have shown little impact to flow volumes to the treatment system, modeling of the site for other purposes, including northward flow, may be very sensitive to recharge. Recharge may be best incorporated as a calibration parameter and will need to be adjusted as other parameters described in this report are changed.

HEAD CALIBRATION

Original Analysis (Steps 1 and 2)

The comparison of observed and computed heads in the unconsolidated deposits (layer 1) shows a very good agreement. When computed and observed values at each observation point are plotted as shown on the left side of Figure 8, the slope is 0.995, very close to the optimal 1.0. The use of pilot points to define the horizontal hydraulic conductivity has allowed for the heterogeneity required to closely reproduce the measured heads.

The comparison of observed and computed heads in the bedrock (assumed layer 2) is not as close, as shown in the right plot on Figure 8. The range of measured heads is smaller, so most wells match within a few feet, but when computed and observed values at each observation point are plotted, the slope is 0.337 indicating that the head change across the site in the bedrock is about 3 times that calculated in the model.

Discussions during the October 2015 meeting with Barr Engineering included a description of a sensitivity analysis where the deepest layers of the bedrock were given lower hydraulic conductivity. In these runs, the gradient in the bedrock observation points was closer to that measured, though there was little impact to the flows to the pits from groundwater. A formal report of this sensitivity analysis was not provided or examined during the meeting or afterward.

An additional concern with the head calibration is the timing of the observations. Nearly all the layer 1 wells were calibrated to the average of 10-15 observations between the fall of 2011 and the fall of 2013. Almost all of the bedrock wells were calibrated to a single observation made in December 2006. However, Barr Engineering reported that the OB bedrock wells each have 9 years of head data showing little variation. The data presented in the modeling report shows 10 data points for each of these wells, spread over a period of 7 years (ending in 2013, so 9 years of data was probably available as of the October 2015 meeting) with data ranges for head between 1 and 3.4 ft and no apparent trends.

The model report indicates that the calibration was biased towards solutions that did not show significant flooding of the land surface (head above ground surface elevation) at a set of control points. According to statements from Barr Engineering, these control points were not positioned to avoid wetlands areas. We would note that a large portion of the area is classified as wetlands and the head could be close to or above the ground surface. Barr Engineering showed a figure in the October 2015 meeting which compared the locations of wetlands to places where the model showed heads above ground surface elevation (Barr, 2015c). Most of the locations where the model shows heads above ground surface correlate to wetlands areas. There are many wetlands areas where heads are not above ground surface, however.

Some adjustments to the calibration would make the model more defensible. These adjustments would include calibration to two separate periods (2006, and 2011-2013) with appropriate Peter Mitchell pit levels, close attention to gradients as well as slopes, and comparison of wetlands delineations to areas where the computed head is above the ground surface. These improvements may impact the groundwater flow to the pits, but are unlikely to significantly impact the flow to the treatment facility, which is dominated by flows not captured by this MODFLOW model, such as precipitation, overland runoff, and snowmelt. However, these improvements would be necessary for most other purposes to which the model may be applied.

Update (Step 3)

The GLIFWC reviewers noted that the calibration period was different from the period with maximum water level in the Peter Mitchell pit (used in the calibration model) and from the period when data was collected for estimation of baseflow. While baseflow should not change significantly over long periods of time when there are no significant changes to the flow characteristics of the basin, and the data shows little change to heads at the mine site despite significant changes to Peter Mitchell pit levels, any future modeling of the site should ensure that the correct pit levels are used in calibration.

GEOLOGY

Original Analysis (Steps 1 and 2)

The model report states that the bottom of layer 1 was set equal to the bedrock-surface elevation (Barr, 2014a). The following sentence says that the "bottom elevations of some layers were modified slightly in some locations to prevent portions of the layer from going dry during model simulations." The bottom elevation of layer 1 drops suddenly at the boundary of the mine site by a distance of 10 to 30 m to a constant elevation of 456 m. In the northern corner of the model, the bottom elevation of layer 1 drops by 20 m and then again by 10 m to a minimum elevation of 426 m. (See Figure 9.) Possibly the bottom elevation was adjusted as mentioned above, to keep cells from going dry. Regardless, this pattern for the bedrock elevation surface seems unlikely and the significantly greater thickness of the relatively more permeable surficial materials could impact the volume of water conveyed horizontally from the boundaries to the area of interest in the upper layer, or the volume of water conveyed vertically to the bedrock.

Barr Engineering stated that bedrock is actually deeper to the north of the site, though the change would not be as sudden as the model shows. They also pointed out, reasonably, that there is no sudden deflection in the model-calculated head contours at the steps in bedrock elevations. Although this sudden change is not supported by the data and may impact flow to the mine pits, it is unlikely to have an impact significant enough to overpower other, larger contributors to the treatment facility flow, notably snowmelt.

The hydrogeology report (Barr, 2014b) indicates that flow in the bedrock is mostly limited to the upper portions of the rock where fractures are more prevalent and where the weight of overlying rock has not compressed fractures and bedding planes. The division of the Virginia

Formation into two sections to represent different hydraulic conductivity for the shallow and deep portions is a useful way to represent the expected flow differences at varying depths. However, the variation in hydraulic conductivity is minor, with a difference of only a factor of 4. Decrease of deep layer hydraulic conductivities in all bedrock layers may help prevent substantial vertical flows and particle tracks which extend into the deepest layers.

Fractured bedrock systems are often quite heterogeneous and sometimes anisotropic. This is supported by the wide ranges of hydraulic conductivity values obtained from pump tests as presented in the Phase I, II, and III hydrogeologic investigations (Barr, 2006a, 2006b and 2007a). Although there is insufficient data to include this heterogeneity in the model, the uncertainty can be accounted for by running multiple simulations with a range of hydraulic conductivity values. This would be especially important for the Duluth Complex and Virginia Formation which will be intersected by the NorthMet excavations.

Although no sensitivity analysis has been run on anisotropy in the bedrock, it is unlikely to impact groundwater flow to the pits enough to overpower other, larger contributors to the treatment facility flow, notably snow melt. Barr Engineering further stated that the PolyMet geologist believes that the water-bearing fractures were created from glacier loading and unloading and cooling, so the directionality would be more random. And, because the Viriginia is a metasedimentary layer, it may have fractures along strike, which would be orthogonal to groundwater flow.

The Phase I hydrogeologic investigation (Barr, 2006a) presents the results of a number of pump tests in the Duluth Complex. The calculated hydraulic conductivity values vary over several orders of magnitude. When plotted against the depth of the well, there is a loose correlation ($R^2 = 0.6$), with the highest values being calculated from the shallowest wells (See Figure 10). This is reasonable given the fact that fractures would be more plentiful and less compressed nearer the ground surface. The report states the high hydraulic conductivity values occur in wells nearest the outcrop of the Virginia Formation and the tests might be influenced by the more permeable Virginia Formation. Since the shallower wells are generally nearer the outcrop, it is hard to determine which option is correct.

The regional model used a hydraulic conductivity value for the Duluth Complex which was close to the geometric mean of all the data. For the calibration of the local-scale model, a much lower value was used, which more closely matched the data from deep wells, further from the Virginia Formation outcrop. It might be more reasonable to split the Duluth Complex at around a depth of 500 ft and apply a higher hydraulic conductivity near the surface and a lower value at depth.

Sensitivity analyses investigating the impact of bedrock elevation, anisotropy and lower hydraulic conductivity on deeper portions of the bedrock would be useful analyses if the model is to be used for other purposes. For the stated purpose of this model, these sensitivity analyses would not be expected to change the treatment facility design because groundwater flow is only one of several sources of flow to the facility.

CONSTANT HEAD BOUNDARIES

Original Analysis (Steps 1 and 2)

The majority of the cells around the boundaries of the model for layers 1 through 5 were defined as constant heads set from the results of the regional model. The regional model was significantly simplified (one layer representing bedrock, no-flow boundaries, etc.) and so there is some uncertainty in the assignment of the heads on the boundary of the local scale model. The sensitivity analysis presented in the draft Groundwater Modeling report, Appendix B of RS22 (Barr, 2007b) discusses the impact of variations on some key model parameters to both the calibration and the dewatering flow predictions. The specified heads at the boundary are listed as Type II sensitivity, meaning changes to the boundary heads had a significant impact on calibration, but an insignificant impact on predictions. This type of sensitivity is sometimes judged less important than some other types because the parameter values are considered to be constrained by the calibration. However, in this case, there may be a need to run some additional scenarios. If a different, but reasonable set of constant heads were selected for the boundary, the calibration could likely be repeated and result in a different set of hydraulic conductivity values that produce a reasonably well calibrated model. If these models were then used to predict the flows into the excavations, the flow rates might be significantly different but would probably not overpower the other inflows to the treatment facility. If the model is to be used for other purposes (including the investigation of northward flow), this type of sensitivity analysis may be important.

ADDITIONAL CONCERNS AND UNCERTAINTIES (STEP 3)

A number of uncertainties or concerns with the model were raised by other reviewers, but were not mentioned during Steps 1 and 2 of this review. This section will discuss some of these comments.

WETLANDS

Grand Portage comments (February 2015) show a concern about the designation of the wetlands as precipitation fed instead of groundwater fed. While an opinion on this issue is outside the scope of this review, it should be noted that the model could be run with either type of wetlands included explicitly.

SPRINGS AND SEEPS

Grand Portage comments (February 2015) indicate that the groundwater model has failed to include springs and seeps in the model domain. This review has uncovered no available data on either the locations or flow rates of any springs or seeps in the area. If the data exists, they could certainly be added to the model. If their flow rates are large enough, they may impact the results of the northward flow analysis described below, but they would be unlikely to have any significant effect on flows to the pits during operations.

STORAGE PARAMETERS

Regarding the concern about selection of specific storage and specific yield values for an unconfined aquifer, we concur with the Co-lead response (Co-lead Agencies, March 2015). Specific storage, which is a measure of water released due to aquifer compressibility is commonly several orders of magnitude lower than specific yield, a measure of water released due to dewatering of a section of unconfined aquifer.

TOP LAYER TYPE

The Barr model report states that the top layer of the model was defined as a confined type for model stability during calibration. They cite a recommendation from a USGS report (Hill, 1998) as the basis for this adjustment. (Note that USGS, the author of this report, is also the developer of MODFLOW.) This change to the model layer type was a concern in the Grand Portage (December 2015) comments.

Modeling a layer as confined does not “produce the illusion of … an endless supply of water.” (Grand Portage, December 2015). When a layer is modeled as confined, the transmissivity is calculated using the thickness of the cell. With an unconfined layer, the transmissivity is calculated using the saturated thickness. Thus, as long as the water table stays close to the ground surface this is probably an appropriate approximation. There is also a similar adjustment to storage values, but since the calibration model was steady state, storage values are not used. The operations and closure models were run with all layers set to type convertible, which allows MODFLOW to switch the layer type between confined and unconfined based on the elevation of the computed water table in each cell.

The Hill report recommends running the model with the top layer confined and unconfined (or convertible) to ensure the results are similar. This type of sensitivity would have been useful to ensure no significant effect from this simplification.

UPHILL FLOW IN PARTRIDGE RIVER

The Grand Portage comments (February 2015) state that the MODFLOW model shows the Partridge River flowing upstream. MODFLOW does not model surface water. It models only sources and sinks to the groundwater. As the Partridge River was a possible source or sink to groundwater it was included as a boundary condition. The calculation of flow between the river and the groundwater requires the input of river stage, river bottom elevation and conductance of river bottom sediments, which together determine the flow volumes to or from the groundwater in each cell of the model. The river bottom elevation was determined from the DEM (LiDAR) data. Because of the sparse nature of the elevation data and the meandering nature of the river, some places showed downstream cells with higher bottom elevations than neighboring upstream cells. This impacts the flow to the groundwater in each cell, but does not mean water is flowing uphill. On a large-scale model like this, small differences in flow rates cell-to-cell will not significantly impact the final results of the model.

Barr performed a sensitivity analysis on the setup for the river boundary condition. When the river boundary condition was reset, paying special attention to river elevation and ensuring that the stage continuously dropped along the length of the river in a downstream direction, the impact was minor. The recalibrated hydraulic conductivity values changed by about 1%. The recalibrated river conductance values changed by about 5%. The baseflow changed only slightly and there was practically no change to the flow rates to the pits (Barr, 2015e).

ALLEGED MANIPULATION OF MODEL RESULTS

The Grand Portage Band Comments (Grand Portage, December 2015) contain a comment that there is a discrepancy between the Year 20 drawdown reported in RS-22, Appendix B, Draft-03 (Barr Engineering, 2008) and the model results. NAP reviewers found some differences between the current model output and that shown in Appendix B of RS-22, but they are not as severe as the discrepancy described in the comments. We find no evidence of manipulation of the data. RS-22, Appendix B is a report of an old version of the model, which has been updated. This appendix was written in 2008 and it is not surprising that additions and updates to the model over the last 7-8 years have resulted in differences in the model results. Further, the drawdown figure is not included in recent versions of the model report, probably due to the fact that the analysis of area of influence is not a purpose of the model and the model is not valid for that determination.

NORTHWARD FLOW

As mentioned in the introduction to this document, the Barr MODFLOW mine site model is not an appropriate tool for predicting post-closure flows, including to the north. As the main purpose of the model is estimation of pit flows during operations, the controversy surrounding northward flow was considered outside the scope of this review during the first two steps. However, given that GLIFWC reviewers have used this MODFLOW model as the basis for their contention that northward flow should be included in the transport modeling (GoldSim), the following is a summary of the arguments for and against northward flow with comments.

ARGUMENTS FOR NORTHWARD FLOW:

1. As described by GLIFWC in a 9/11/2015 email, there will be a steep northward gradient between closure levels at NorthMet and future levels at Peter Mitchell. Although the two mines will be less than 8000 ft apart, the current plans show that the head difference at closure of the PolyMet mines will be slightly more than 100 ft; at closure of the Peter Mitchell pits, the head difference will be nearly 300 ft; and at the long-term Peter Mitchell level, the head difference will be nearly 100 ft. That is a gradient of between 0.01 and 0.04 ft/ft.
    a. NAP response: This steep gradient would seem to indicate a high possibility of significant flow to the north.
2. GLIFWC argues (GLIFWC, December 2015) that the figures presented by Barr in their September 2015 memo showing drawdown at an open pit mine in the Mesabi Iron Range indicate that a mound would be formed in the surficial aquifer around the Peter Mitchell pits large enough to encompass the PolyMet pits.
    a. NAP response: This argument is weak since the figures have no horizontal scale (beyond a statement in the caption giving the approximate length of the figure) and show insufficient data points to accurately pinpoint the location of the groundwater divide. Further, these figures show a different mine in a different location with differences of hydrogeology and topography. They should not be used alone to determine the size of a cone of depression that would form around the NorthMet mine pits.

ARGUMENTS AGAINST NORTHWARD FLOW:

1. The most recent imagery and elevation terrain data available from Google Earth (9/2013) shows the Area 003 East pit, which is quite deep (about 1350 ft) and dry except for a small pond at the bottom. This low, dry pit is less than 2.5 miles from the Partridge River and seems to have a head difference from the river of about 250 ft. This may indicate that if northward flow is likely, it would already be happening, yet the water level data at the Northmet mine site indicates flow is towards the southeast in both the surficial aquifer and the bedrock (Barr, December 2014, Large Figure 17).
2. Aerial photography (Google Earth) shows plants and greenery at the very edge of the Peter Mitchell pits, even decades after excavation operations began. The plant life is

visible in all available historical photos, which represent a variety of seasons over two decades. This would indicate that drawdown in the surficial aquifer, at least, is minimal or not laterally extensive, and that northward flow in the surficial aquifer is unlikely after closure of both mines.

3. Elevation data on Google Earth as well as data provided in the GLIFWC comments (Table 1, GLIFWC, Dec 2015) and a Barr Memo (Table 2, Barr Engineering, September 2015) show a large difference in water level elevation between the Peter Mitchel Area 003 West pit and Area 003 East pit (labeled pits 6 and 5, respectively, in the GLIFWC table) in 2011 and 2013. The head difference exceeds 50 ft although the horizontal distance between the edges of the two pits is approximately 600 ft. Although Cliffs Natural Resources, who operates the Peter Mitchell pit mining, declined to provide additional details, there is no evidence that a cutoff wall (such as a grout curtain) exists between the two pits other than the wall of rock that has remained in place to support a road. There is also no evidence of pumping into the west pit to maintain a high water level. If the high water level in the west pit can be maintained naturally while the east pit is pumped dry, this would indicate very little drawdown in the bedrock. Note that the Peter Mitchell pits are excavated from the Biwabik Formation (BIF), which is different from the Virginia Formation, through which any northward flow from the NorthMet mine pits would pass. The hydrogeologic information provided by Barr Engineering states that the BIF is more conductive than the Virginia, but there is no known local pump test data in the BIF to support this statement and there is significant variability in the pump test data in the Virginia. The conductivity values used in the model for the two units are similar (0.87 ft/d and 0.31 ft/d). If the two units are similar, the high water level in the west pit during dewatering in the east pit (if maintained naturally) would indicate low probability of significant volumes of northward flow from the NorthMet pits after closure.

4. Aerial photos (Google Earth) of the currently dry Peter Mitchell pits over a range of seasons for 2 decades show mostly dry bedrock with only a few seeps visible and few areas of vegetation which would indicate moisture. This would suggest a relatively small amount of seepage into the pits and a small probability of significant northward flow from the NorthMet pits after closure. As mentioned previously, the Peter Mitchell pits are excavated from the BIF, while northward flow from the NorthMet pits would pass principally through the Viriginia formation.

5. Barr Engineering showed that bedrock wells installed near the proposed NorthMet mine site demonstrated no impact from a 40-ft drop in water levels in Peter Mitchell Area 003 East pit between 2007 and 2015. Figure 4 of the September 2015 Barr memo (Barr Engineering, September 2015) compares the heads in 5 bedrock wells and the pit level. This data shows no response in the bedrock wells to the drawdown in the pits and indicates a low probability of significant volumes of northward flow from the NorthMet pits after closure.

    a. GLIFWC refutes this argument (GLIFWC, December 2015) by pointing out that the Peter Mitchell Area 003 West pit was full during the dewatering of the East pit and that this high water could negate the effect of the empty pit. If the outflow from the West pit is sufficient to offset the dewatering effects of the East pit, it would seem that a large amount of water would need to be pumped into the West pit to maintain the high water level. The GLIFWC comments refer to "MODFLOW modeling by GLIFWC" to show this effect. If this reference is to the Barr model with Peter Mitchell pit levels adjusted by GLIFWC, this is an inappropriate use of this model. For the reasons described in this document, the Barr model was designed to look at pit inflows and should not be applied to any other purpose.

b. GLIFWC also refutes this argument (GLIFWC, December 2015) by stating that the regional trends should be considered in analyzing the effect of East pit dewatering on the bedrock wells. Unfortunately, there is no known bedrock head data in the region with enough data between 2007 and 2015 to show a trend (or lack of one). However, it would take an enormous regional rise in bedrock water levels to counteract a 40-ft drop in heads at the East pit. This rise in water levels would significantly impact the volumes of water removed to dewater the Peter Mitchell pits.

6. The EIS project managers published a memo considering the possibility of northward flow (NorthMet, October 2015) which described a 2D MathCad model of the possible northward flow path and concluded that 8 in/yr of recharge would result in a mound between the two pits and prevent northward flow from the NorthMet mine pits.

    a. GLIFWC argues that the ground surface and bedrock surface elevations used in this model are 25-50 ft too high (GLIFWC, December 2015).

        i. NAP comment: The MathCad model is highly simplified and does not account for the variability of the top of bedrock or the ground surface.

        ii. NAP comment: GLIFWC seems to have made the comparison at a different cross-section than that used in the MathCad model.

    b. GLIFWC argues that 8 in/yr of recharge could only be achieved if the water table is well above land surface (GLIFWC, December 2015).

        i. NAP comment: Both the MathCad model and the GLIFWC analysis are highly simplified.

    c. NAP comment: The location of the interface between the Virginia Formation and BIF formation seems to be placed incorrectly in the MathCad model. This probably has little impact on the results, including the recharge value that would cause the mound to form.

    d. NAP comment: The idea that 8 in/yr of recharge can or does occur in the area between the two pits is contrary to the conceptual model described in the model report for the mine site MODFLOW model. It is more than four times the recharge values used in the MODFLOW model.

SUMMARY

It is important to note that although many reviewers have stated that the bedrock hydraulic conductivity values used in the MODFLOW model are likely too low, points 3, 4, and 5 above may mean the hydraulic conductivity values used in the model are too high.

Due to the contradictory evidence for and against northward flow, we believe it is reasonable to more closely investigate the issue. It is outside the scope of the Corps' Section 404 permit authority under the Clean Water Act to model the groundwater to analyze northward flow. The Recommendations section below provides some suggestions for additional modeling should others wish to assess the probability of this flow path. The results of the modeling may direct any future field efforts which may be necessary.

RECOMMENDATIONS

The existing model is considered to be sufficient for estimating inflows to the pits for the purpose of sizing a treatment facility. There may be significant error in those estimates due to some of the simplifications made to the model, as described above, but these errors are expected to be minimal compared to the large volumes of water entering the pits from rainfall, surface runoff, and especially rapid snowmelt. The treatment facility is to be built in modules so that unexpectedly large flow rates can be treated by quickly adding additional modules.

We recommend the following changes to the model (some may have minimal impacts to the model results):

1. Account for higher hydraulic conductivity near the surface by splitting the bedrock materials and applying higher hydraulic conductivity to the upper layers and lower values to the lower layers of the model.
2. Add Langley Creek (tributary of Dunka River).
3. Adjust the top of bedrock elevations to match available data.
4. Add Hundred Mile Swamp and other wetlands areas to match available wetlands delineations.
5. Add any springs or seeps for which there is data on location and/or flow rate.
6. Change the top layer type to convertible.
7. Add boundary conditions to the edges of layers 6, 7 and 8 to help ensure horizontal flow.
8. Adjust the river bottom elevations and associated stage to ensure continuous downstream reduction.
9. Split the surficial aquifer into 2-3 layers to allow better simulation of wetlands and the pump test in the Phase 3 Hydrogeologic Investigation. If necessary, the increased grid size may be offset by removing or combining some deeper layers.

Recalibrate the model to the following data:

1. Steady state calibration to 2006 water levels with the Peter Mitchell pits set at their estimated 2006 levels.
2. Steady state calibration to average 2011-2013 water levels with the Peter Mitchell pits set at their estimated 2011-2013 levels.
3. Transient calibration to pump tests presented in the Phase 1, 2, and 3 Hydrogeologic Investigations. (May require refinement of the grid.)
4. Transient calibration to the 2007-2011 period when the Area 003 East Peter Mitchell pit was being dewatered and five bedrock wells showed no impact. Note that other pits should be at their 2007-2011 levels, including the Area 003 West pit which was full during this period.
5. On all runs, use particle tracking to ensure mostly horizontal flow with no diving particles.
6. On steady state simulations 1 and 2 (above), ensure that the observed vs. calibrated head plots show nearly 1:1 slopes.
7. Ensure that the water level is below ground surface except in delineated wetlands areas.
8. Any runs which show widely variant water levels in Peter Mitchell Area 003 East and Area 003 West pits should be able to maintain the high water level in the west pit with only inflows approximately equal to average runoff volumes.

With the above adjustments and calibrations, the model will be more accurate and defensible in predicting the pit inflow rates during operations. It may also be a better tool for other purposes for which a model may be used, including investigation of long-term closure conditions. Like all models, it will still contain uncertainty and a robust sensitivity analysis, similar to that described below, will still be necessary.

Once the model has been recalibrated, a closure model can be built to investigate the probability of northward flow. This may be steady state at closure levels for both mines, or it may be transient, showing the closure of one mine, filling of the pits, closure of the second mine and the filling of those pits. Because of sparse data and wide differences of opinion among the outside reviewers, the following sensitivity analyses are recommended. In each case, the change should be made and the model recalibrated as above. If a model can be found that shows northward flow and meets all the calibration requirements, then, additional study on the question of northward flow would be recommended.

1. Baseflow – A range of values should be considered at SW003, from 0.51 cfs recommended by Barr Engineering, to 3.4 cfs recommended by Grand Portage.
2. Recharge – A range of values should be considered from the low values used in the original MODFLOW model, to the much larger values in the USGS (2007) estimate.
3. Wetlands types – Wetlands, notably the Hundred Mile Swamp should be included as precipitation fed and (separately) as groundwater fed.
4. Boundary heads – These heads were originally set by a simplified regional model calibrated to heads only in the mine site area. They should be adjusted up and down and some runs should allow for vertical flow. It may be easiest to change these to use the general head package.
5. Hydraulic conductivity – There is limited data on hydraulic conductivity in some units. The data that does exist shows wide variability. Adjustments within wide ranges will ensure the consideration of all possibilities. It will be especially important to adjust the vertical hydraulic conductivity of the surficial aquifer – even beyond the range considered reasonable by Barr Engineering.
6. Horizontal anisotropy – Adjustment of the horizontal anisotropy in the bedrock layers will account for the possibility of directional fracturing which could affect both flow direction and flow rates between the pits.

These sensitivity analyses will help bound the conclusions and quantify the model uncertainty. They should help commenters understand the impact of their suggestions to the model results and may help determine the likelihood of northward flow. If any of these recommendations result in a model which is well calibrated and shows northward flow from the NorthMet pits towards the Peter Mitchell pits, then it may be concluded that additional study is warranted. These studies should also help direct future field data collection efforts, should the uncertainty be substantial.

CONCLUSIONS

In general, the model is reasonable for the purpose for which it was designed (to estimate groundwater flow into the NorthMet mine pits during operation as one input to the sizing of the treatment facility). There are a number of updates and sensitivity analyses which might improve the quality of the model and its ability to answer a wider range of questions. Many of these are discussed in this report. However, since groundwater flow to the pits is a very small percentage of the total flow that is expected at the treatment facility and the requirements for estimating volumes of water to be treated are very conservative, it is unlikely that any estimate of groundwater flow would cause a significant change to these volumes. Further, during the October 2015 meeting, the design of the treatment system was revealed to be modular, such that errors in estimates of flow could be easily accounted for by adding additional modules to the system.

The model is currently not a valid tool for investigation of northward flow after closure of both the proposed NorthMet mines and the existing Peter Mitchell pits. Modeling and analysis of this issue is outside the Corps' Section 404 Permit authority under the Clean Water Act. This review makes some recommendations for updates to the model, additional calibration runs and sensitivity runs that could help determine the probability of significant northward flow, should others wish to pursue the study of northward flow using this model. In the case of considerable uncertainty (multiple sensitivity runs show northward flow while others do not) additional modeling and analysis as described in the Recommendations section may help determine what types of field studies should be used to reduce uncertainty and better investigate the possibility of northward flow.

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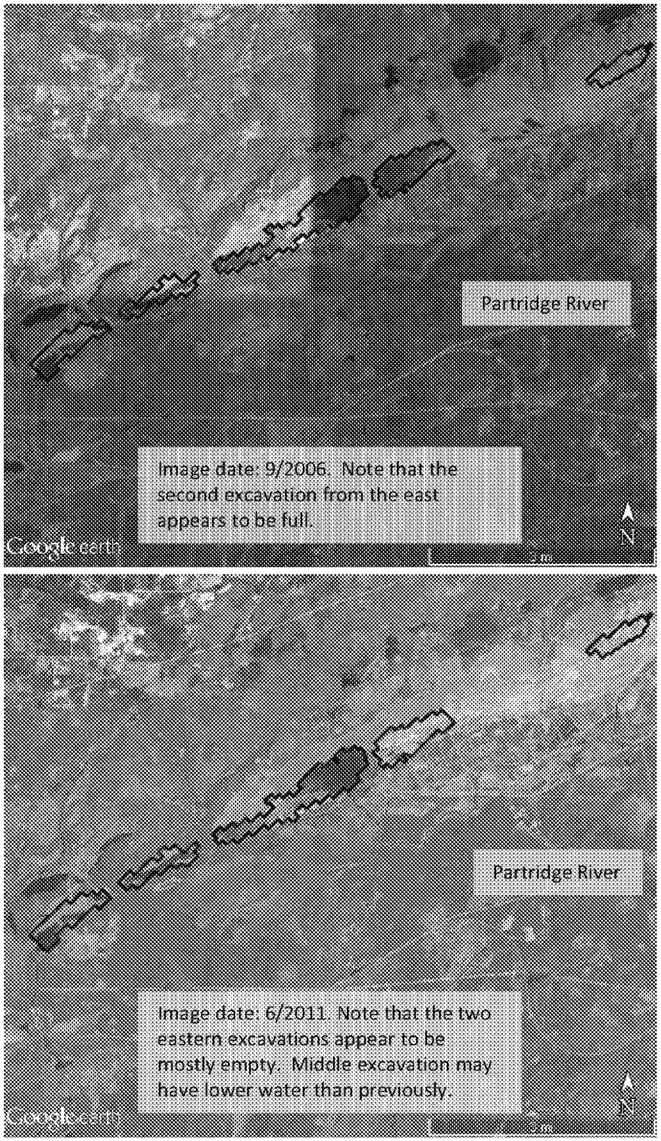
FIGURES



Legend

- Rivers
- Outline of MODFLOW Cells representing Peter Mitchell Pits

Notes:

Aerial photos are from Google Earth, Pro.

River polylines are from USGS National Hydrographic Dataset.

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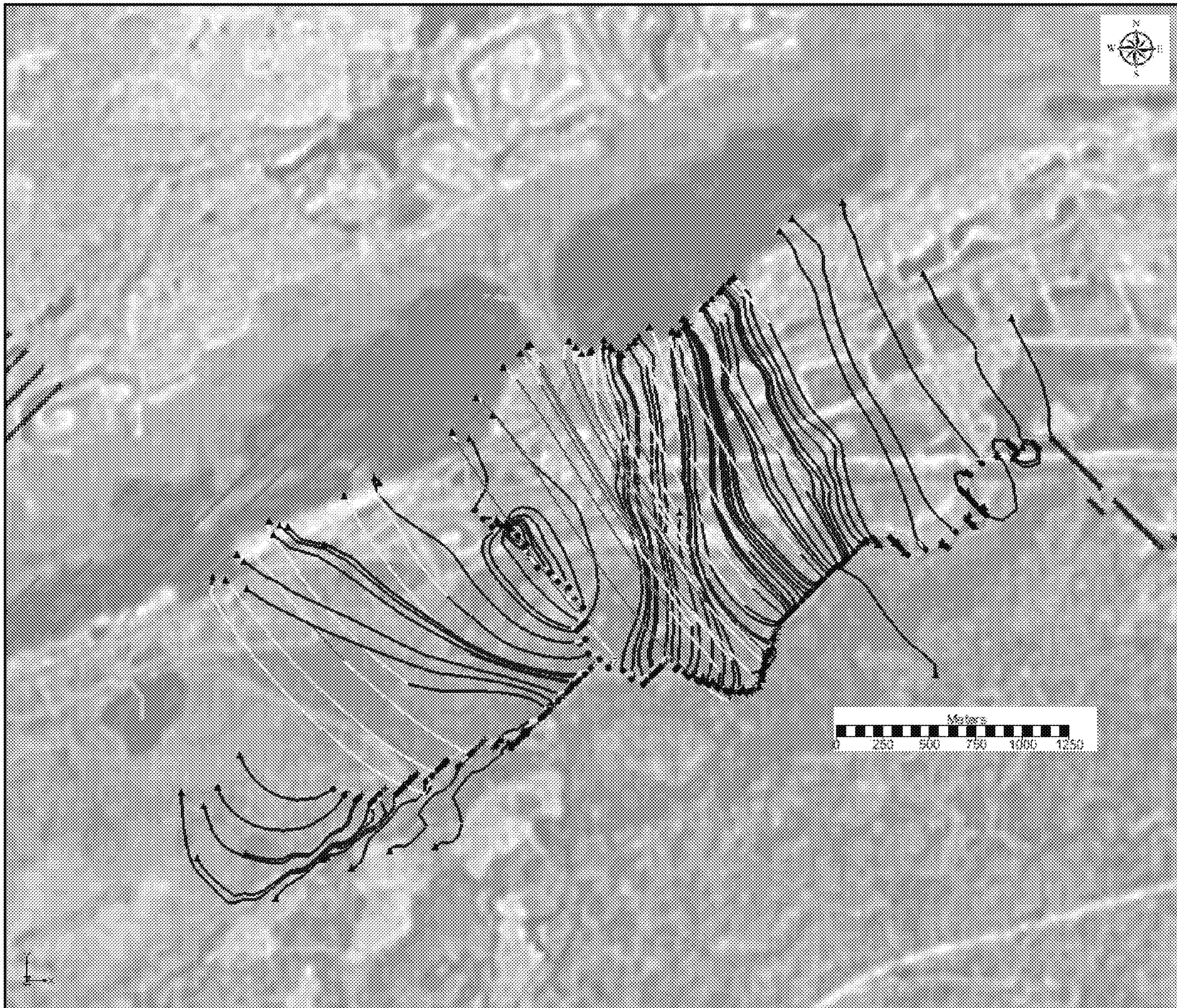
Historic Aerial Photos of Peter Mitchell Excavations

NorthMet Mine MODFLOW Review

Figure 1

August 2016



Legend

- River
- Specified Head Cell (Peter Mitchell Pits)
- River Cell
- MODPATH backwards particle paths
- MODPATH particle start points
- MODPATH particle end points

The color of the paths indicate the layer of the model through which the particle is passing, as follows:

- Layer 1
- Layer 2
- Layer 3
- Layer 4
- Layer 5
- Layer 6
- Layer 7
- Layer 8

Notes:

Aerial photo is from ESRI.

River polylines are from USGS National Hydrographic Dataset.

Particles are running backwards from gaining cells on the upper reach of the Partridge River back to their source.

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Philadelphia District

Backwards MODPATH Particle Tracks from Gaining Cells of Upper Reach of Partridge River

NorthMet Mine MODFLOW Review

Figure 2

August 2016

Legend

River

Specified Head Cell

River Cell

Depth of water above ground surface (m)

5.0
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0
-5.0

Notes:

Aerial photo is from ESRI.

River polylines are from USGS National Hydrographic Dataset

Negative depths indicate water below ground surface.

Areas not covered by colors have values beyond the range of -5m to 5 m.

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Difference between ground surface and water level in calibration model, layer 1.

NorthMet Mine MODFLOW Review

Figure 3

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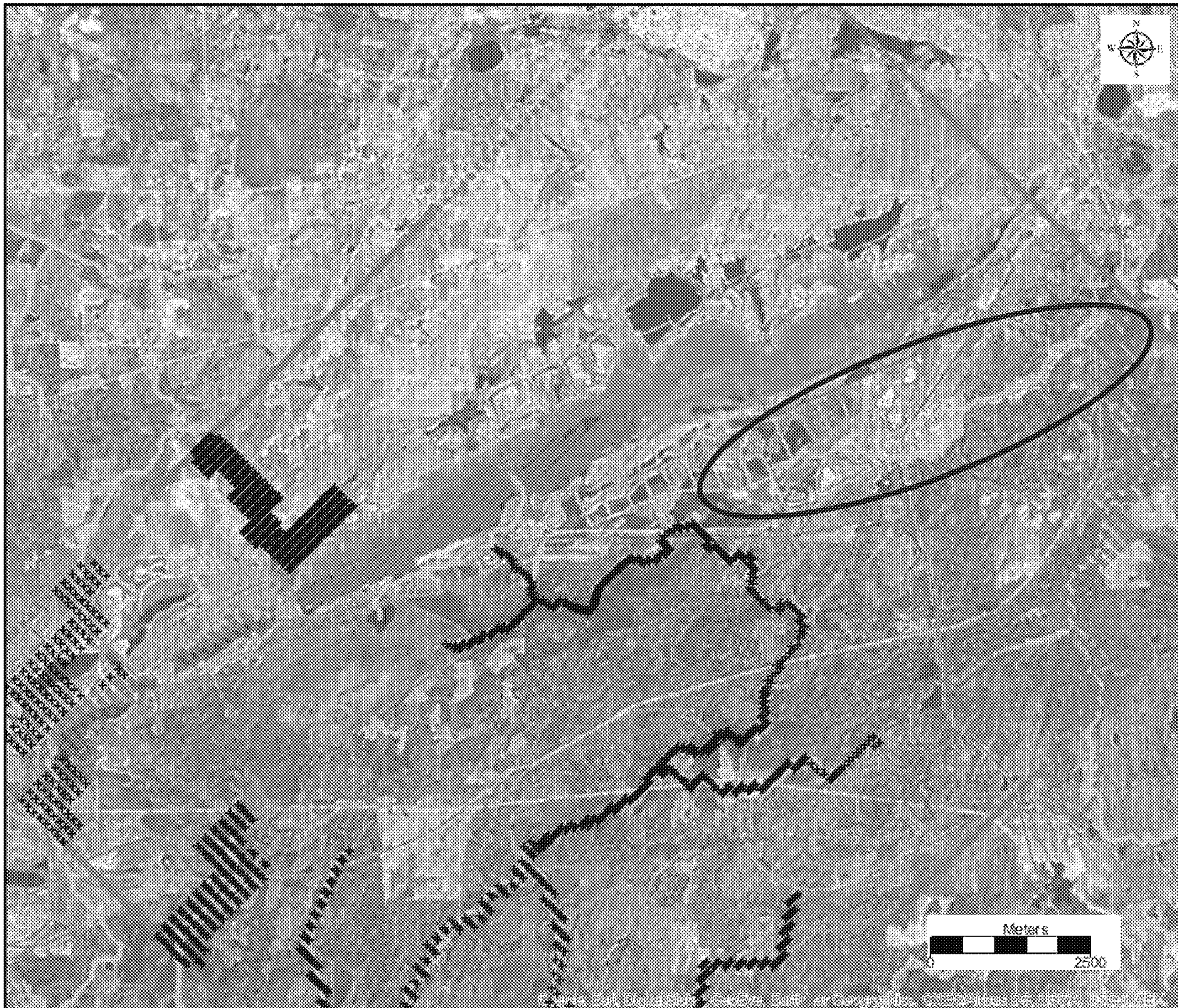

Legend

River

Specified Head Cell

River Cell

Notes:

Aerial photo is from ESRI.

River polylines are from USGS National Hydrographic Dataset.

The red oval indicates the section of the Dunka River system which has not been included in the model.

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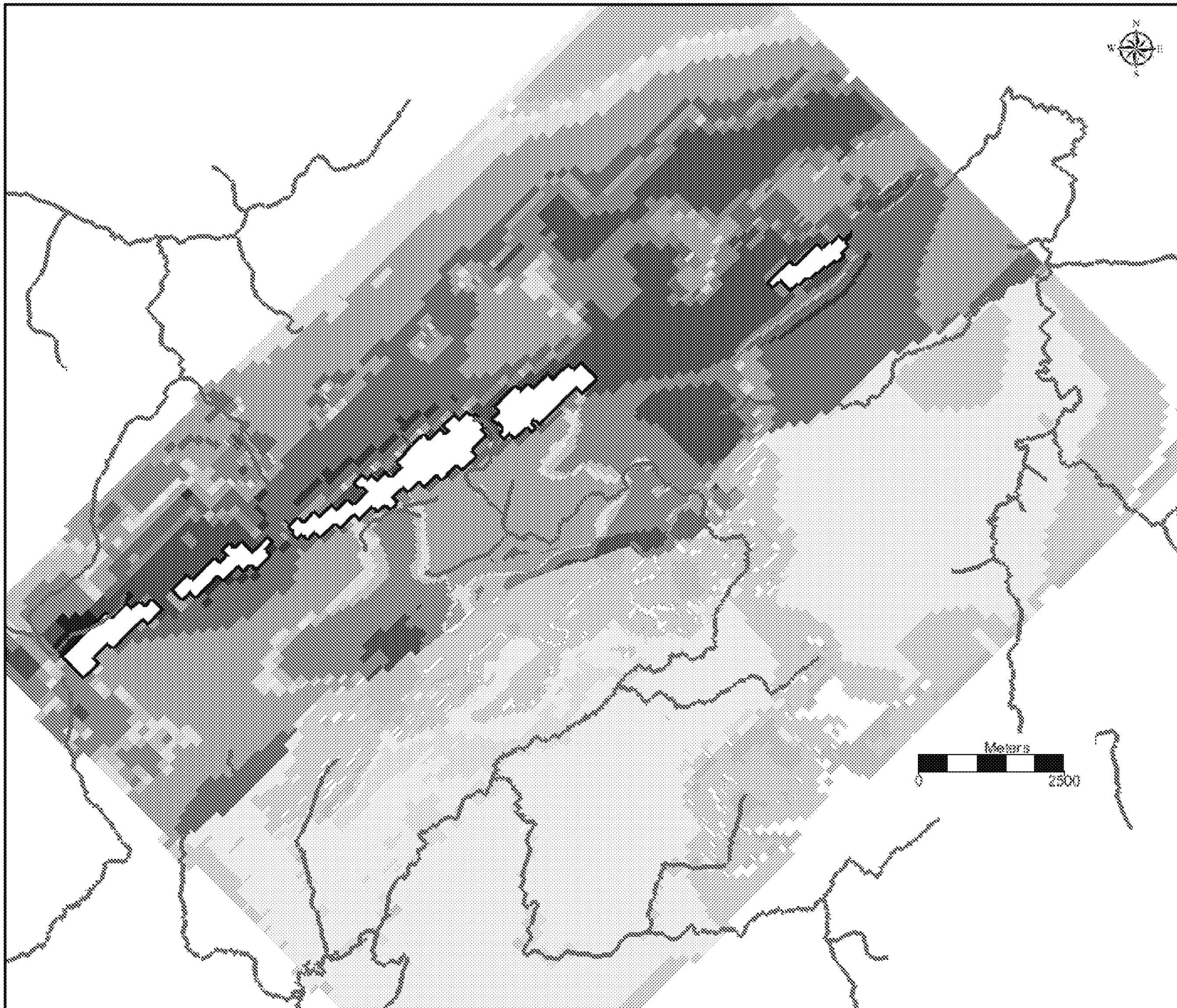
Location of Missing Section of Dunka River Section

NorthMet Mine MODFLOW Review

Figure 4

August 2016



Legend

Rivers

Outline of MODFLOW Cells representing Peter Mitchell Pits

Infiltration to Bedrock (in/yr)

- 10.0 to 34.0
- 1.0 to 10.0
- 0.1 to 1.0
- 0.01 to 0.1
- 0.001 to 0.01
- 0.0001 to 0.001

Flow of Water Upward from Bedrock to Unconsolidated Deposits (in/yr)

- 10.0 to 34.0
- 1.0 to 10.0
- 0.1 to 1.0
- 0.01 to 0.1
- 0.001 to 0.01
- 0.0001 to 0.001

Notes:

Vertical flow rates are calculated by dividing the lower face flow volume from layer 1 (contained in MODFLOW's cell-by-cell flow file) by the area of the cell and then converting the units.

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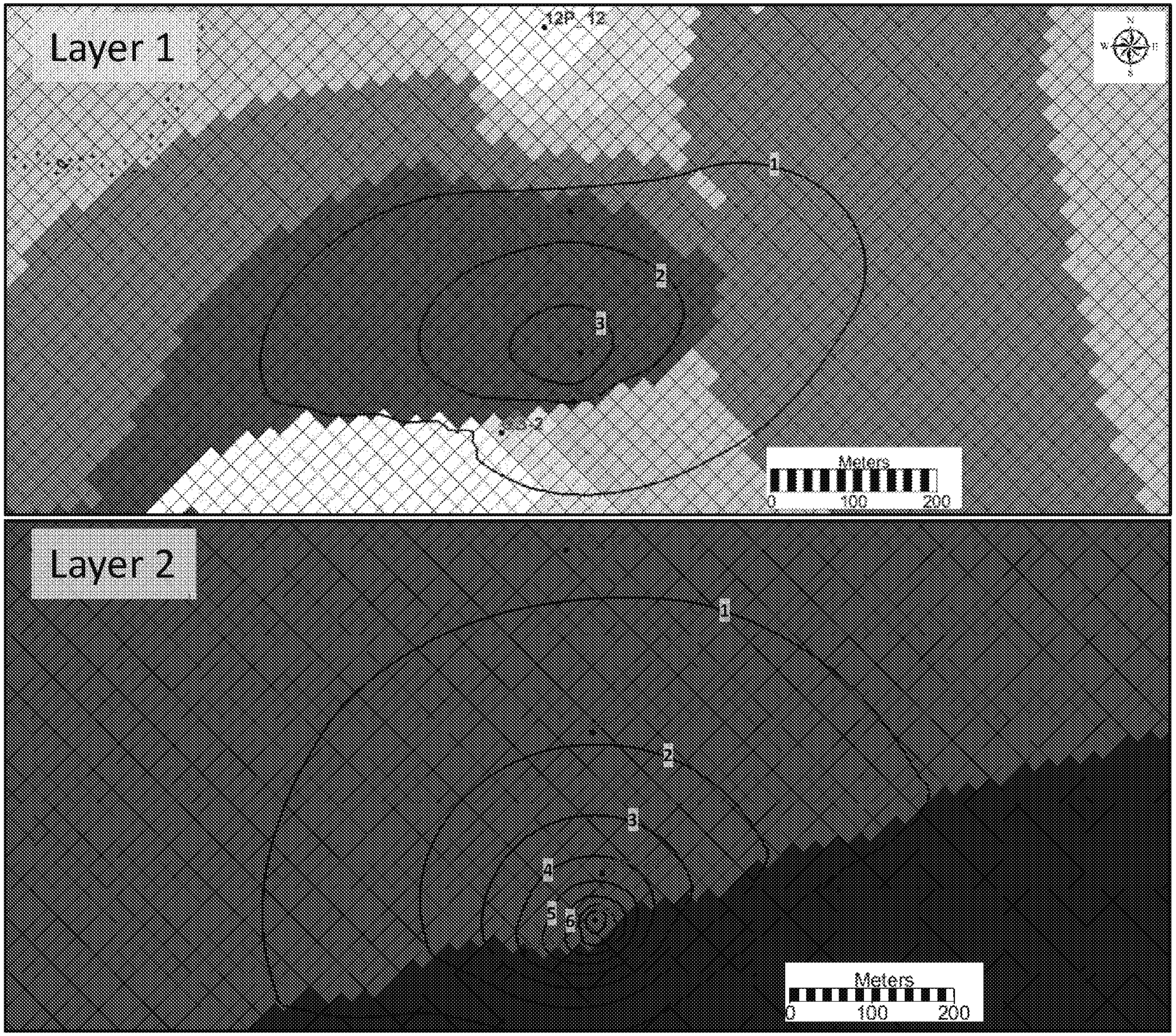
Model Results: Movement of Water between Layer 1 (Unconsolidated Deposits) and Layer 2 (Bedrock)

NorthMet Mine MODFLOW Review

Figure 5

August 2016



Legend

•2P Well (Pumping or Observation)

—1— Maximum Drawdown Contours (1 m intervals)

Grid Cell Horizontal Hydraulic Conductivity (m/d)

- 0 – 0.003 (Duluth Complex)
- 0.003 – 0.01 (Giants Range Granite)
- 0.01 – 0.03 (Lower Virginia Formation)
- 0.03 – 0.1 (Upper Virginia Formation)
- 0.1 – 0.3 (Biwabik Iron Formation)
- 0.3 – 1.0
- 1.0 – 3.0
- 3.0 – 10.0
- 10.0 – 30.0
- 30.0 – 68.3

Notes:

Although the bedrock formations are listed in the hydraulic conductivity legend, some areas of the unconsolidated sediments were assigned hydraulic conductivities in the bedrock ranges. This area of the model does not have bedrock outcrops. The bedrock designations are applicable only to layers 2 through 8.

The locations of 12P/12, 2P and 20P/20 have been estimated. The location of OB-2 has been adjusted to place it in the Duluth Complex.

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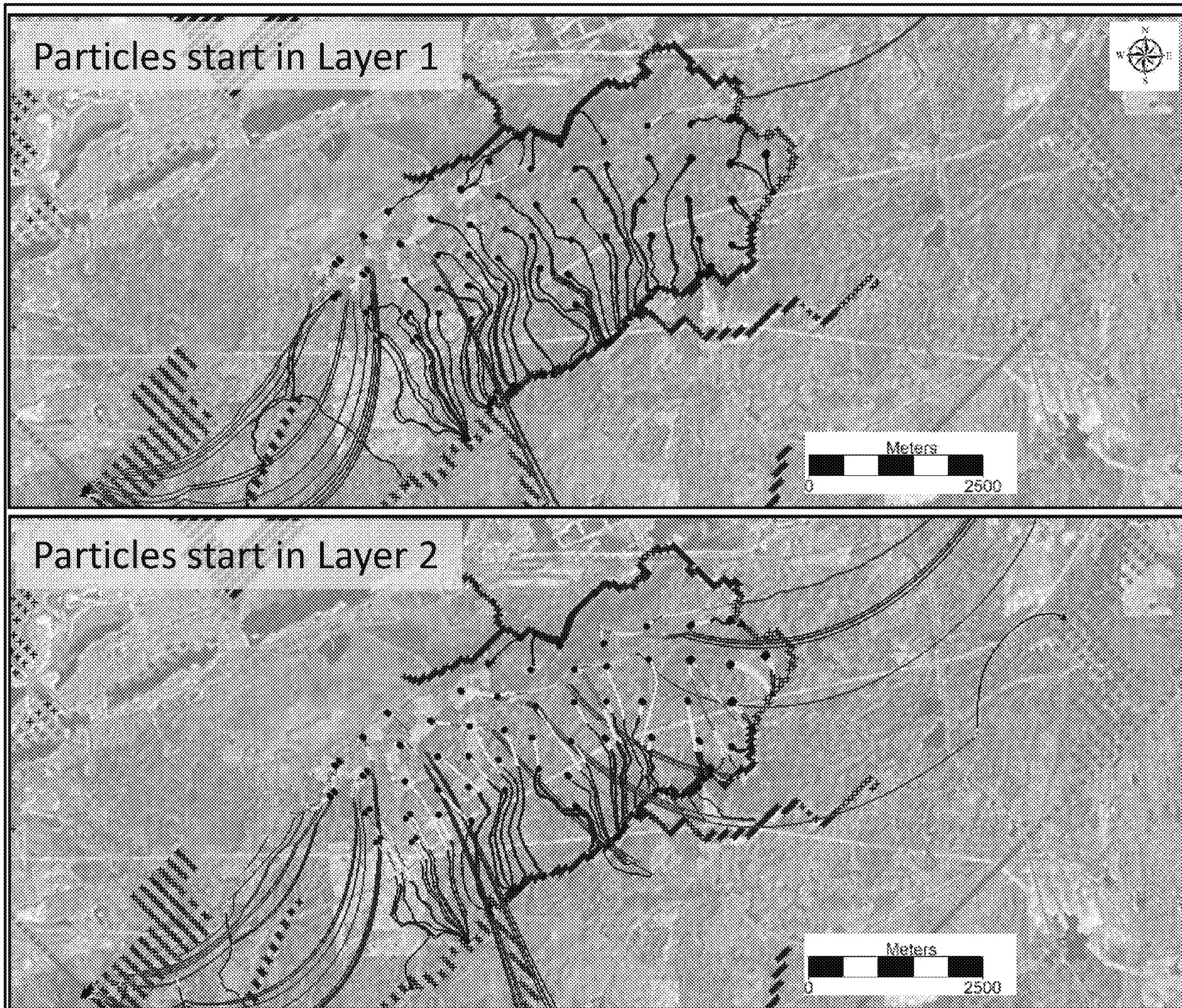
Maximum Drawdown for P-2 Pump Test as Simulated in the Calibration Model

NorthMet Mine MODFLOW Review

Figure 6

August 2016



Legend

- River
- Specified Head Cell
- River Cell
- MODPATH forward particle paths
- MODPATH particle start points
- MODPATH particle end points

The color of the paths indicate the layer of the model through which the particle is passing, as follows:

- Layer 1
- Layer 2
- Layer 3
- Layer 4
- Layer 5
- Layer 6
- Layer 7
- Layer 8

Notes:

Aerial photo is from ESRI.

River polylines are from USGS National Hydrographic Dataset

Particles are running forwards from cells in the mine area towards their ultimate destination.

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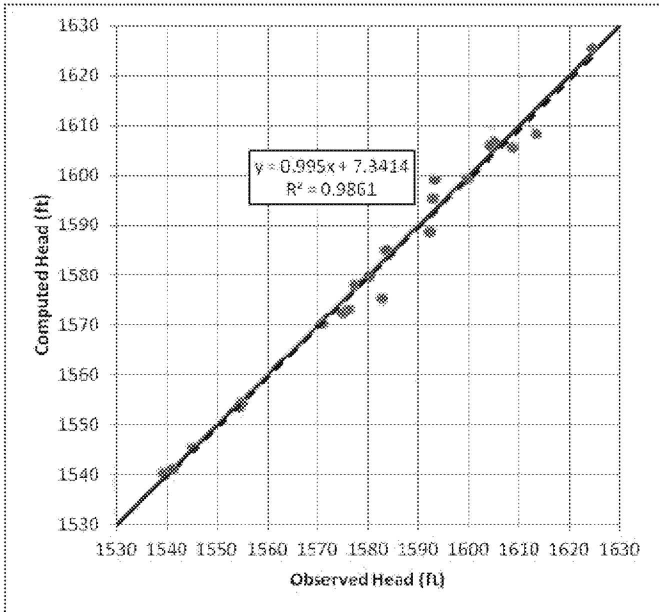
Forward MODPATH Particle Tracks from Mine Area Cells

NorthMet Mine MODFLOW Review

Figure 7

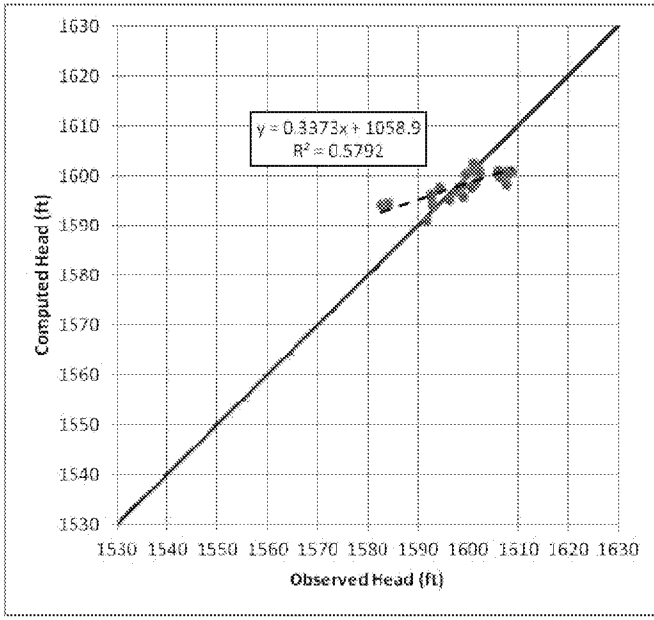
August 2016

Unconsolidated Deposits



Mean Error = 0.627
Mean Abs. Error (MAE) = 2.12
Root Mean Square (RMS) Error = 2.87
Sum of Squared Residuals = 173.01
Range of Observations = 85.3 ft
RMS as % of Range = 3.4%
MAE as % of Range = 2.5%

Bedrock



Mean Error = 1.34
Mean Abs. Error (MAE) = 3.52
Root Mean Square (RMS) Error = 4.85
Sum of Squared Residuals = 682.57
Range of Observations = 26.1 ft
RMS as % of Range = 18.6%
MAE as % of Range = 13.5%

Legend

- Observation Well
- Trend Line
- 1:1 Slope Line (Optimal)

Notes:

These plots are created from the data provided in Large Table 3 in the Modeling Report.

The black dotted lines are best-fit trendlines calculated by Excel. The equation is provided to show the slope. An optimal calibration will have a slope of 1.0

Note that the R^2 value presented on the plot is the correlation between the observations and the trend line and is not a comparison to the optimal 1:1 line.

Statistics calculated on the residual are shown beneath each plot.

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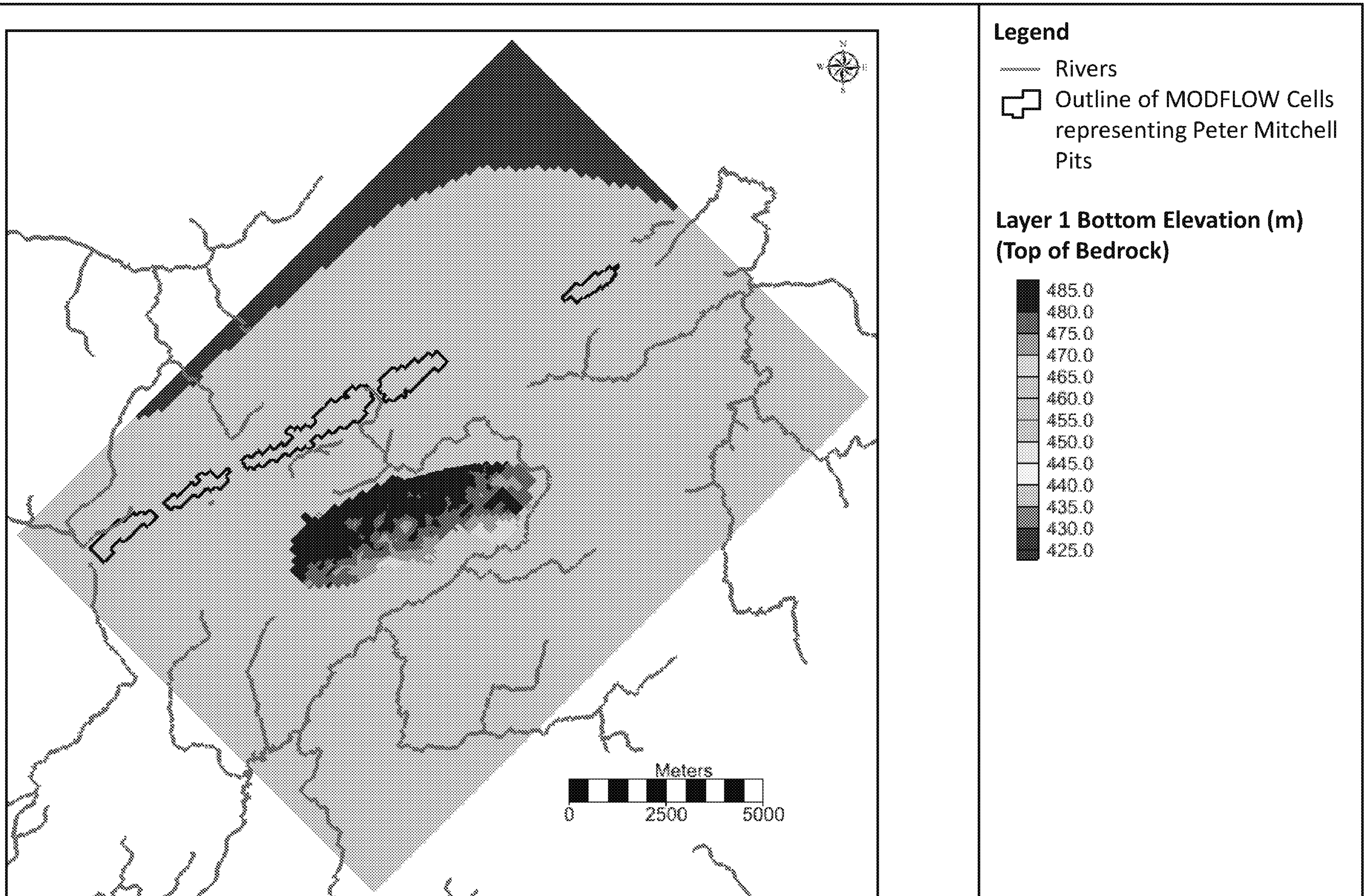
Calibration Statistics Separated for Unconsolidated Deposits and Bedrock

NorthMet Mine MODFLOW Review

Figure 8

August 2016



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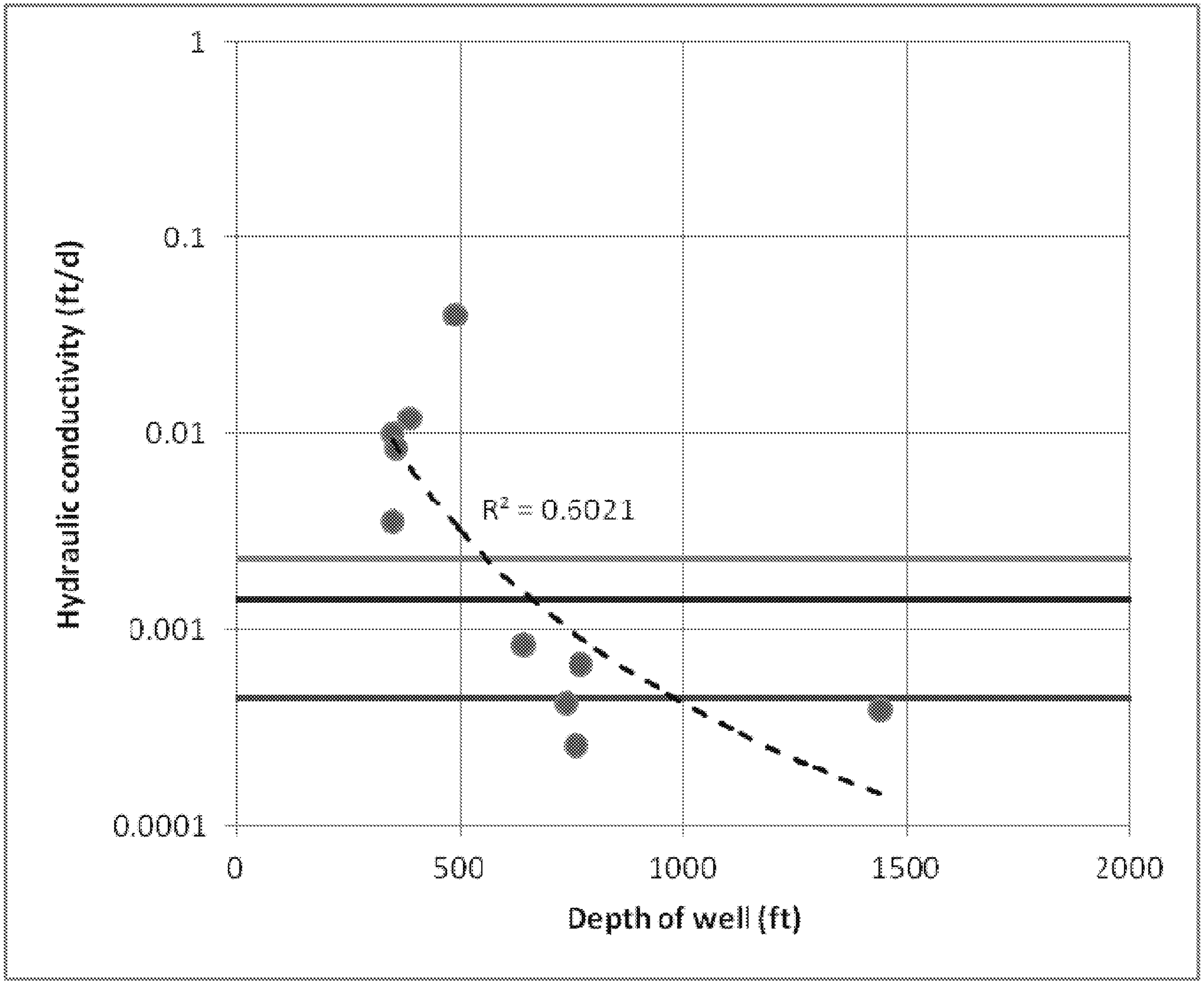
Elevation of Top of Bedrock Used in MODFLOW Model

NorthMet Mine MODFLOW Review

Figure 9

August 2016



Legend

- Test Well
- Geometric Mean (0.0023 ft/d)
- Trend Line
- Horizontal Hydraulic Conductivity Used in Regional Model (0.0014 ft/d)
- Calibrated Horizontal Hydraulic Conductivity Value for Local Scale Models (0.00044 ft/d)

Notes:

This plot is created from the data provided in Table 6 from RS02.

The black dotted line is the best-fit power trendline calculated by Excel.

Colored horizontal lines show various conductivity values and statistics used for the Duluth Complex during the modeling process.

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Duluth Complex Pump Tests Compared to Well Depth

NorthMet Mine MODFLOW Review

Figure 10

August 2016